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THESIS

A PERSISTENT PLANNING MODEL FOR EXPLOSIVE ORDNANCE DISPOSAL TRAINING AND EVALUATION UNIT TWO

by

Edward A. DeWinter

September 2012

Thesis Advisor: Emily M. Craparo
Second Reader: W. Matthew Carlyle

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A PERSISTENT PLANNING MODEL FOR EOD TRAINING AND EVALUATION UNIT TWO

Edward A. DeWinter
Commander, United States Navy
B.A., Vanderbilt University, 1995

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September 2012

Author: Edward A. DeWinter

Approved by: Emily M. Craparo
Thesis Advisor

W. Matthew Carlyle
Second Reader

Robert F. Dell
Chair, Department of Operations Research

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ABSTRACT

The Explosive Ordnance Disposal Training and Evaluation Unit TWO (EODTEU TWO) trains Explosive Ordnance and Disposal (EOD) and Mobile Diving and Salvage (MDS) companies and platoons prior to worldwide deployments. This thesis describes EODSKED, an optimization model designed to assist EODTEU TWO in scheduling platoons that optimizes the use of limited resources and maximizes training value. EODSKED produces an optimized schedule that respects a large number of manpower and materiel resource constraints; such a schedule is difficult to achieve with the current manual scheduling process. Schedule modifications are often required after a schedule has been published; therefore, EODSKED incorporates persistence constraints to generate new schedules that match existing schedules closely.

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LIST OF ACRONYMS AND ABBREVIATIONS

BRAC	Base Realignment and Closure
COI	Course of Instruction
CPSKED	Combatant Primary Event Schedule
EOD	Explosive Ordnance Disposal
EODGRU	Explosive Ordnance Disposal Group
EODSKED	Explosive Ordnance Disposal Scheduling Tool
EODTEU TWO	Explosive Ordnance Disposal Unit Two
GAMS	General Algebraic Modeling System
IED	Improvised Explosive Device
MDS	Mobile Diving and Salvage
OSAF	Optimal Stationing Army Forces
OTHCAM	Optimal Transition HC Allocation Model
SOF	Special Operations Forces
ULT	Unit Level Training

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EXECUTIVE SUMMARY

The Explosive Ordnance Disposal (EOD) Training and Evaluation Unit TWO (EODTEU TWO) trains EOD and Mobile Diving and Salvage (MDS) platoons and companies prior to worldwide deployments. EODTEU TWO trains several types of platoons, each with different training objectives and requirements. Training consists of courses of instruction that vary in length from 20 to 51 working days; these courses of instruction are divided into various modules, require instructors, equipment and ranges that must be scheduled in advance. Consequently, EODTEU TWO is constrained by manpower, training facilities, resources and equipment, and calendar training days. These constraints limit the number of EOD platoons that can be trained at any given time.

This thesis describes EODSKED, a scheduling decision support tool that assists EODTEU TWO in producing a training schedule for EOD platoons and companies. It consists of a Microsoft Excel workbook coupled with an integer linear program implemented using the General Algebraic Modeling System (GAMS). EODSKED determines when platoons should begin training, in which training pipeline they should be placed, and which resources should be allocated to their training. In doing so, EODSKED attempts to maximize the training value received by EOD and MDS platoons by training platoons during their ideal training window and alongside platoons within the same company while simultaneously minimizing a series of penalties designed to optimize resource allocation.

Training schedules often require changes after their publication due to changes in input data such as deployment schedules, platoon requirements, equipment availability, and other requirements for the schedule. EODSKED incorporates these changes and builds a new schedule that closely replicates as much of the original schedule as possible. EODSKED ensures that any modifications are incorporated in a new schedule while maintaining a high degree of persistence (i.e., agreement with a prior schedule) and fidelity to ensure smooth and flexible operations. This is accomplished through a series of penalties placed on deviations from the original schedule.

We find that EODSKED is significantly easier to use than the legacy manual planning process, and that the addition of persistence constraints simplifies replanning schedules in the face of disruptions. EODSKED is now in use by EODTEU TWO.

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I. INTRODUCTION

A. PROBLEM

U.S. Navy Explosive Ordnance Disposal (EOD) technicians are responsible for removing and mitigating the hazards posed by ordnance (EODTEU TWO, 2011). EOD personnel are trained to render safe various types of ordnance, including chemical, nuclear and improvised explosive devices (IEDs) (Navy Expeditionary Combat Command, 2012). Extensive training is required for EOD personnel in these mission areas; prior to their deployment an EOD platoon conducts training with Explosive Ordnance Disposal Training and Evaluation Unit ONE (EODTEU ONE) or TWO (EODTEU TWO). The mission of EODTEU ONE and TWO is to "develop and maintain standardized, formal unit level training and refresher program for all Atlantic/Pacific Fleet EOD personnel" (Commander Explosive Ordnance Dipsosal Group Two, 2011). Scheduling the required training and allocating resources to it for multiple platoons simultaneously are not an easy task and manual planning consumes a tremendous amount of time.

EODTEU TWO, in Fort Story, VA, approached the Naval Postgraduate School Operations Research Department in 2011 for assistance in developing a tool to assist with the creation of training schedules. This thesis describes EODSKED, a mathematical model that functions within an Excel-based decision support tool that has been designed to streamline the entire scheduling process and facilitate tracking and reporting of resource utilization by EODTEU TWO.

B. BACKGROUND

The U.S. Navy's EOD program traces its origins back to World War II, when the Navy realized the need for the safe removal of sophisticated ordnance (NAVSEA, 2012). EOD forces are organized into two EOD Groups (EODGRUs) located in San Diego, CA and Little Creek, VA. Under each EODGRU are EOD Mobile Units (EODMUs), EOD

Training Evaluation Units (EODTEU), Mobile Diving and Salvage Units (MDS), and various EOD companies, platoons, and detachments (Navy Expeditionary Combat Command, 2012).

EODTEU TWO's primary mission is to prepare Navy EOD platoons, Expeditionary Navy Divers, and Mobile Diving and Salvage Companies for deployment throughout the world. The command has the ability to train up to seven EOD platoons and one Salvage Diver Company simultaneously in support of Carrier Strike Group, Expeditionary Strike Group, Mine Countermeasures Forces, Naval Special Warfare Forces, Special Operations Forces (SOF), and contingency operations. These platoons conduct different training based on their type of deployment and mission area. In addition, the command provides advanced proficiency training and specialized training for EOD personnel and other civilian agencies such as U.S. Secret Service (EODTEU TWO, 2011).

In calendar year 2010, EODTEU TWO conducted over 200 resident courses involving over 7,000 instructor days and over 15,000 student days. The majority of the training completed at EODTEU TWO is Unit Level Training (ULT) designed to properly train deploying mobile platoons and companies. In order to satisfy the basic training phase requirement of the Readiness Training Cycle that must be completed prior to deployment, each EOD platoon and company completes a 20- to 51-day training pipeline consisting of a sequence of ULT-specific Courses of Instruction (COIs) or training modules. COIs offered at EODTEU TWO include Combat First Aid, Surface Ordnance and Improvised Explosive Devices, Chemical/Biological and Nuclear Ordnance Hazards, and several others (EODTEU TWO, 2011).

Platoons are assigned to training pipelines composed of the various training modules. These training modules require various manpower and materiel resources and must be completed by a specific date to meet deployment requirements. The exact timing of a platoon's completion of training relative to its deployment date affects the overall value of the training it receives; however, resource constraints limit the number of platoons and companies that EODTEU TWO can train at a given time, resulting in a difficult scheduling problem that must be overcome in order for EODTEU TWO to function effectively.

C. CURRENT SCHEDULING PROCESS

EODTEU TWO currently uses Microsoft Project as a visualization tool to manage EODTEU TWO's training schedule. Their manual scheduling process is highly complex and involves consideration of multiple resource and precedence constraints. The goal of this process is to create a schedule for the year that maximizes the use of limited resources to the greatest extent possible while determining feasible pipelines and start dates for all platoons and companies.

The first step in creating a schedule manually is to obtain the deployment dates from EODGRU for the individual platoons and companies. Deployment dates dictate the deadlines by which platoons and companies must complete training. Additionally, some platoons and companies must conduct additional training such as nuclear training at national laboratories prior to arriving at EODTEU TWO. The completion date of this training is fixed in advanced and determines when a platoon can begin training at EODTEU TWO. These constraints define a window of feasible start dates for each platoon and company. Once these feasible start dates are established, a rough schedule is put into place that deconflicts certain high priority range areas used by EODTEU TWO. Certain platoons such as SOF platoons are given higher priority during this process. Finally, each platoon's exact start dates and pipeline are determined while taking into account several resource constraints.

EOD training is highly resource intensive, and EODTEU TWO has limited resources available such as trucks, boats of a certain size or personnel with particular qualifications. To use these resources efficiently, scheduling personnel attempt to match platoons with similar training requirements and train them together as a company. While some platoons arrive as a paired company and receive an additional training benefit from training together, others arrive separately and are paired purely for efficiency reasons.

For example, two platoons completing training as a company would require only a single classroom and instructor in order to complete a lecture session; if trained separately, they would require two.

Scheduling personnel take steps during the scheduling process to ensure that no resource is over-utilized. Other resource constraints are also considered; for example, certain members of EODTEU TWO must travel to Rota, Spain for a portion of a training pipeline. This adds additional personnel resource constraints to the planning process in order to minimize travel. Once all of these resource constraints are taken into account, the final schedule is displayed on a Gantt chart and manually checked to ensure that resource constraints are not violated and that platoon's feasible start and end dates are observed (see Figure 1).

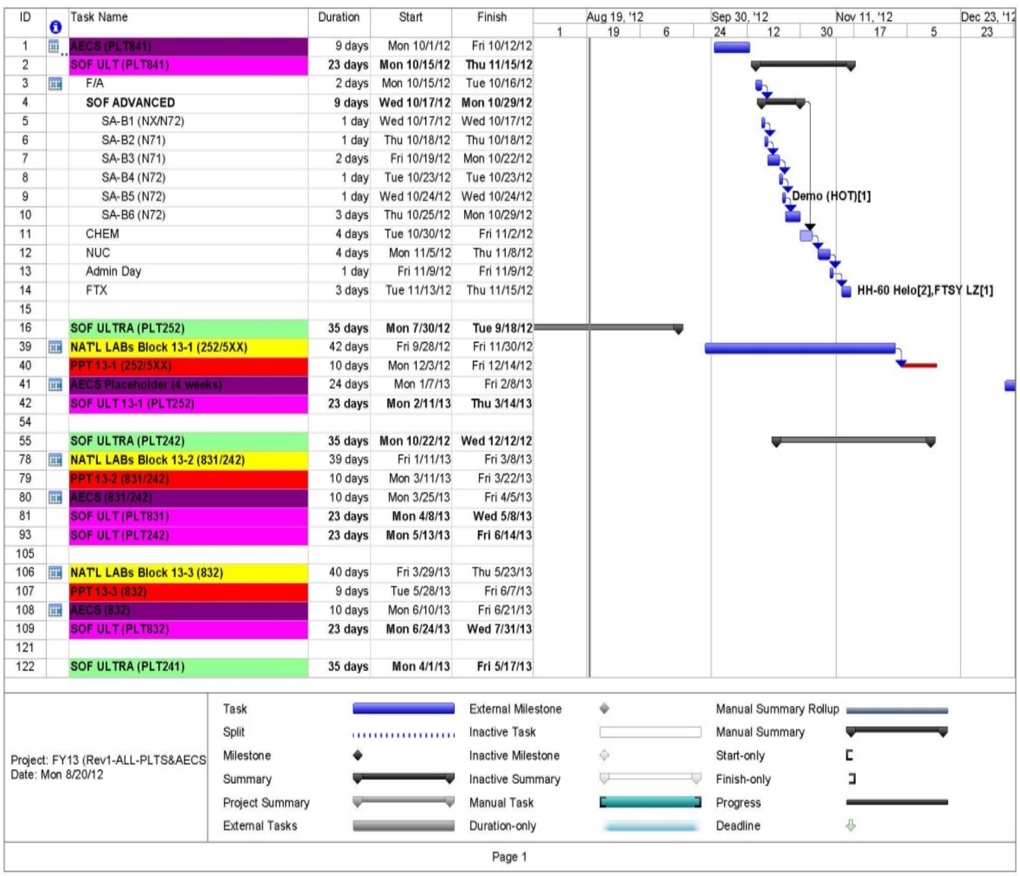


Figure 1. A manually-created schedule displayed using a Gantt chart (From McElligott, 2012)

D. LIMITATIONS TO THE MANUAL SCHEDULING PROCESS

Creating a complex schedule manually is time-consuming and does not guarantee that an optimal use of resources is accounted for in the final schedule. In particular, the complexity of the resource constraints encountered by EODTEU TWO mean that compromises must be made in solution quality in order to ensure feasibility. EODTEU TWO has over 100 different types of materiel and personnel resources, and its training syllabus contains 18 different types of pipelines and over 20 different modules. Given this complexity, the best way scheduling personnel have to avoid conflicts or shortages in resources or shortages is to manually ensure separation between similar training events that share common resources. This means two modules of the same type cannot be conducted at the same time by different platoons or companies. For example, it is not possible to have one platoon or company start the First Aid module while another platoon is still in training in that module. Although this technique is effective, it is overly conservative in many cases.

Frequently, changes occur to platoons' deployment dates or to resource availability after a schedule is produced. Changes to deployment dates could impact a platoon's feasible training days, or unforeseen losses of manpower or materiel resources could result in an existing schedule becoming infeasible. When such changes occur, a new schedule must be created manually. This replanning process can be extremely time-consuming, and large perturbations to an existing schedule can occur. Indeed, it is well known that a new schedule created in response to such changes can differ greatly from a previously published schedule if the existing schedule is not taken into account in the planning process (Brown, Dell, & Wood, 1997).

EODSKED addresses these limitations in several ways. EODSKED has the ability to track daily resource consumption and allows for modules to overlap when sufficient resources are available. EODSKED significantly alleviates the difficulties that develop when deployment dates change by allowing the user to fix portions of the original schedule, such as a specific platoon's start date, for use in the new schedule. This allows the new schedules to deviate as little as possible form the original if desired by the schedule planner.

A model that accounts for an existing schedule and attempts to minimize disruptions to this schedule while meeting new requirements is said to incorporate persistence. EODSKED incorporates persistence by measuring and penalizing deviations from the original values of certain decision variables in the updated solution. This capability is also useful when EODSKED is used in a rolling horizon fashion; as new platoons request training, they can be incorporated into the end of an existing training schedule with minimal changes to any training that is scheduled in the near term (see Figure 2).

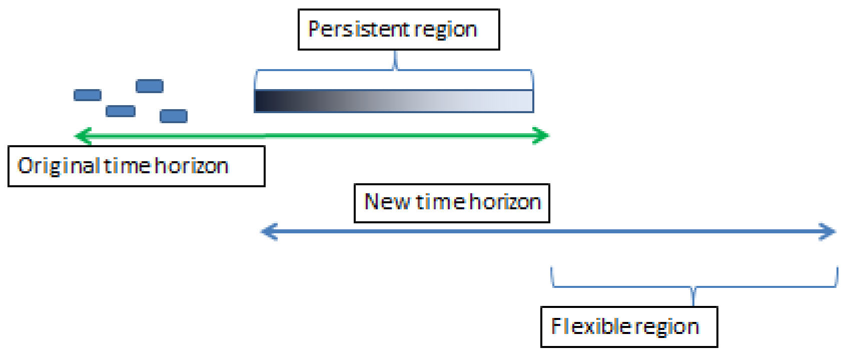


Figure 2. Graphical depiction of the use of persistence in a rolling time horizon. The dark area on the persistence bar indicates the region where penalties on schedule deviations are highest; these penalties decrease with time.

Finally, the manual scheduling process does not automate the tracking of daily resource consumption. Without tracking daily resource consumption it is difficult to determine which resources are critical. Critical resources are those that are in short supply or without which training cannot be completed. EODSKED is capable of tracking resource utilization and producing reports on resource consumption to assist the scheduler in identifying critical resources and possible future resource shortfalls.

E. RELATED WORK

This literature review examines the development of optimization models for scheduling problems, with particular emphasis on models that include notions of persistence or that use integer linear programming.

Brown, Goodman, and Wood (1990) describe a generalized set partitioning optimization model, called Combatant Primary Event Schedule (CPSKED) that automates a manual scheduling process for Atlantic Fleet ships. The scheduling of ships is particularly complex because there are insufficient ship types and associated weapons systems for all of the requested events. EODSKED minimizes the cost set of ship schedules such that the demand for types of weapons systems and ships is satisfied for all planned events. The model shows that optimization of a scheduling process can produce improved ship schedules.

Brown, Dell, and Farmer (1996) discuss the limitations of a manual scheduling process in the context of Coast Guard Cutter scheduling. Manual scheduling is labor-intensive and often provides suboptimal solutions. Brown et al describe an elastic mixed-integer linear programming model called CutS which optimizes a schedule to satisfy the patrol and maintenance requirements for the First Coast Guard District Cutters. The elastic formulation assigns linear penalties to schedules when patrol or maintenance requirements cannot be met. The model produces a schedule in less than two hours; this compares favorably to the two to three days required to create a manual schedule. The model also emphasizes the importance of persistence. The authors show that if persistence is not considered in the model, small changes to the input data can produce large changes to the schedule. Proper consideration of persistence, on the other hand, prevents major revisions of the incumbent schedule when only a small modification is required.

The scheduling problem considered in this thesis can be compared to a personnel assignment model. This scheduling problem maximizes training value by matching platoons and training pipelines while a personnel assignment model maximizes quality of fit by matching assignments to personnel. Enoka (2011) describes an optimized personnel assignment tool that solves an integer linear program based on a multicommodity network flow model. EODTEU TWO's complex resource requirements prohibit use of a network model; however, however, both models use persistence by retaining features of prior solutions when changes occur and require the production of a new schedule or assignment.

The United States Army uses an integer linear program called Optimal Stationing Army Forces (OSAF) that provides optimal Army personnel stationing for a given set of installations (Dell, Ewing, & Tarantino, 2008). The OSAF model minimizes cost in dollars while providing optimal stationing using existing starting locations, a set of installations, and unit requirements. In particular, OSAF was used in the Base Realignment and Closure (BRAC) decisions in 2005. The primary focus of OSAF is to minimize the cost associated with personnel relocations as opposed to EODSKED, which uses an integer linear program to maximize training value in a scheduling process.

Optimal Transition HC Allocation Model (OTHCAM) also uses an integer linear program to create an optimal distribution schedule for helicopter pilots (Culver, 2002). This model minimizes lost flying days with an optimized distribution schedule that accounts for variable training durations, travel times and tour lengths, as well as manpower and aircraft constraints. Our persistent planning model is similar to OTHCAM's approach to developing an optimal schedule while minimizing violations of resource constraints.

II. TRAINING OPTIMIZATION MODEL

A. EODSKED

We now describe EODSKED's mathematical formulation. Note that some parameters, variables, and constraints occur only when a prior solution, denoted as the "existing solution," has already been published by EODTEU TWO. These parameters, variables, and constraints enable EODSKED to incorporate persistence. If no such schedule exists, most of the associated data (penalties, etc.) can be set to zero and these components do not enter into the resulting model.

B. MODEL FORMULATION

Indices

e	EOD platoon.
o, o'	Training option; also called a training pipeline or pipeline option.
d, d', d''	Day. Indices d and d' refer to absolute days within the planning horizon, while d'' refers to relative days within a training pipeline. For example, if a platoon started on d=5, and today is d'=7, then the platoon is on day d''=3 of its pipeline.
r, r'	Resource type. Refers to specific types of pieces or to individual personnel; for example, "Truck, F-350" or "LT John Doe."
k	Resource category. Refers to a genre of equipment that may be needed in a training pipeline. Multiple resources types can fulfill a single resource category requirement; for instance, resource category k = "Truck, Option 1" may be fulfilled by resources r = "Truck, F-350" or "Truck, F-150."
c	Named company consisting of two platoons. A named company receives an improved training experience as a result of training together.
t, t'	Number of teams. Each platoon requires training for a certain number of teams (1-4), and each training pipeline is designed for a certain number of teams.

Index Sets

$d \in START_{e,o}$	Set of days d in which EOD platoon e can start training option o.
$o \in PLAT_e$	Set of training options o that can be undertaken by platoon e.
$e \in CP_c$	Set of platoons e that are part of company c.
$e \in TE_t$	Set of platoons e that require training for t teams.
$e \in FIXALL$	Set of platoons e whose start date and pipeline must be the same as in the existing solution.
$e \in FIXDATE$	Set of platoons e whose start date must be the same as in the existing solution.
$o \in TO_t$	Set of training options o that can train t teams.
$(e,o,d) \in X^{old}$	Set of platoons e that started training option o on day d in the existing solution.
$c \in Y^{old}$	Set of companies c that were paired in the existing solution.
$r \in PEOPLE$	Set of personnel resources

Data [units]

d_e^{old}	Day platoon e began training in the existing solution [day].
$s_{r,r'}$	Number of times that resource r' *is* counted when calculating resources usage for r [resource unit]. Certain resources can be substituted for other resources in sufficient quantites; for instance, two all-terrain vehicles (ATVs) can be substituted for a single rhino vehicle. $s_{r,r'}$ models usage of the resulting "2ATV" resource ($s_{2ATV,ATV} = 2$).
$b_{o,o'}$	=1 if a precedence constraint should exist for pipelines o and o'; 0 otherwise [binary]. (For capturing precedence constraints, i.e., do not utilize a "company-type" pipeline o' unless an appropriate "platoon-type" pipeline o is utilized.)
h	Number of days in the planning horizon [days].
$avail_r$	Baseline availability of resource r [resource unit].
$unavail_{r,d}$	Amount of resource r that is unavailable on day d [resource unit].

$p_{k,r}$ — Models substitutability among resources by indicating the preference for allowing resource r to fulfill a requirement in category k [unitless]. Zero indicates that the resource cannot be used. Nonzero numbers indicate preference; lower numbers are better.

$d_{e,o,d'',k}$ — Number of resources required by platoon e in category k on day d'' of pipeline o [resource units]. For company-type pipelines, this parameter denotes the additional resources required beyond those required by a corresponding platoon-type pipeline.

$we_{e,o,d}$ — Reward for starting platoon e in training option o on day d (selected to target preferred start dates) [unitless].

$wc_{c,d}$ — Reward for pairing the platoons of company c in training on day d [unitless].

$pr_{r,d}$ — Penalty for exceeding the availability of resource r on day d [unitless]. Reflects the cost of obtaining an additional resource unit.

pb_e — Penalty, per day, for starting platoon e before its original start date in the existing solution [unitless].

pa_e — Penalty, per day, for starting platoon e after its original start date in the existing solution [unitless].

pc_c — Penalty for breaking up company c, which was paired in the existing solution [unitless].

$preq_{r,d}$ — Penalty for requisitioning excess resource r on day d, beyond what was requisitioned in the existing solution [unitless].

$pcreq_{r,d}$ — Penalty for cancelling requisition of excess resource r on day d, which was requisitioned in the existing solution [unitless].

$ppw_{r,d}$ — Penalty for assigning personnel resource r to work on day d, when r was not scheduled to work on d in the existing solution [unitless].

$ppc_{r,d}$ — Penalty for removing personnel resource r from work on day d, when r was scheduled to work on d in the existing solution [unitless].

$ER_{r,d}^{old}$ — Number of resource r surpassing availability in the existing solution [resource unit].

$R_{k,r,e,o,d,d''}^{old}$ — Amount of resource r allocated to platoon e which started option o on day d for use on day d'' of the pipeline in category k in the existing solution [resource units].

pe_r — Penalty for exceeding 80% average utilization of resource r over the entire planning horizon [unitless].

Variables [units]

$X_{e,o,d}$	≡ 1 if platoon *e* starts training option *o* on day *d* [binary]
$Y_{c,d}$	≡ 1 if company *c* has two platoons starting training on day *d* [binary]
$R_{k,r,e,o,d,d''}$	Amount of resource *r* allocated to platoon *e* which started option *o* on day *d* for use on day *d''* of the pipeline in category *k* [resource units].
$ER_{r,d}$	Number of resource *r* surpassing availability on day *d* [resource units].
$EXTRA_r$	Amount by which aggregate usage of resource *r* (over the entire planning horizon) exceeds 80% [unitless].
$DER_{r,d}$	Excess units of resource *r* used on day *d*, beyond what was used in the existing solution [resource units].
$CER_{r,d}$	Cancellation of excess units of resource *r* used on day *d*, relative to what was used in the existing solution [resource units].

Formulation

$$
\begin{aligned}
\underset{X,Y,R,ER,EXTRA,DER,CER}{\text{Max}}\ z = & \sum_{\substack{e\\ o\in PLAT_e\\ d\in START_{e,o}}} we_{e,o,d}X_{e,o,d} + \sum_{c,d} wc_{c,d}Y_{c,d} - \sum_{r,d} pr_{r,d}ER_{r,d} - \sum_{k,r} p\left(p_{k,r}\sum_{e,o,d,d''} R_{k,r,e,o,d,d''}\right) \\
& - \sum_r pe_r EXTRA_r - \sum_e \left(pb_e \sum_{d'=0}^{d_e^{old}-1}\left(d'\sum_o X_{e,o,d_e^{old}-d'}\right) + pa_e \sum_{d'=0}^{h-d_e^{old}}\left(d'\sum_o X_{e,o,d_e^{old}+d'}\right)\right) \\
& - \sum_{c\in Y^{old}} pc_c(1-\sum_d Y_{c,d}) - \sum_{r,d}\left(preq_{r,d}DER_{r,d} + pcreq_{r,d}CER_{r,d}\right) \\
& - \sum_{r\in PEOPLE,d'}\left(\left(ppw_{r,d'} - ppc_{r,d'}\right)\left(\sum_{k,e,o,d,d'':d'=d+d''-1} R_{k,r,e,o,d,d''} - ER_{r,d'}\right)\right)
\end{aligned}
$$

Subject to:

$$\sum_{o\in PLAT_e,\, d\in START_{e,o}} X_{e,o,d} = 1 \qquad \forall e \qquad (1)$$

$$Y_{c,d} \le 0.6 \sum_{\substack{e\in CP_c,\\ o\in PLAT_e:\sum_{o'} b(o',o)>0}} X_{e,o,d} + 0.4 \sum_{\substack{e\in CP_c,\\ o\in PLAT_e:\sum_{o'} b(o',o)=0}} X_{e,o,d} \qquad \forall c,d \qquad (2)$$

$$\sum_{e \in TE_{t'}} X_{e,o',d} \le \sum_{e \in TE_t} X_{e,o,d} \qquad \forall d, t' \le t, (o,o') \text{ s.t. } b_{o,o'} = 1 \text{ and } o \in TO_t \text{ and } o' \in TO_{t+t'} \tag{3}$$

$$\sum_r R_{k,r,e,o,d,d''} = d_{e,o,d'',k} X_{e,o,d-d''+1} \qquad \forall e,o,d,d'',k \tag{4}$$

$$\sum_{r'} s_{r,r'} \sum_{e,o,k,d''} R_{k,r',e,o,d,d''} \le avail_r - unavail_{r,d} + ER_{r,d} \qquad \forall r,d \tag{5}$$

$$\sum_{\substack{(e,o): \\ d \in START_{e,o} \\ o \in PLAT_e}} X_{e,o,d} \le 2 \qquad \forall d \tag{6}$$

$$\sum_d \sum_{\substack{(e,o,d'): \\ d' \in START_{e,o} \\ d' < d}} \sum_{\substack{(k,d''): \\ p_{k,r} > 0 \\ d_{e,o,d'',k} > 0}} R_{k,r,e,o,d',d-d''+1} \le \left(0.8 \sum_d avail_r - unavail_{r,d} \right) + EXTRA_r \qquad \forall r \tag{7}$$

$$\sum_{k:d_{e,o.,d'',k}} R_{k,r,e,o,d,d''} = \sum_{k:d_{e,d,d'',k}} R_{k,r,e,o,d,d''-1}$$
$$\forall o : \left| ROTADAYS_o \right| > 0$$
$$d'' \in ROTADAYS_o, e : o \in PLAT_e, d : d - d'' + 1 \in START_{e,o}, r : \sum_{k:d_{e,o,d'',k>0}} p_{k,r} > 0 \tag{8}$$

$$X_{e,o,d} = 1 \qquad \forall (e,o,d) \in X^{old} \,|\, e \in FIXALL \tag{9}$$

$$\sum_o X_{e,o,d} = 1 \qquad \forall (e,o,d) \in X^{old} \,|\, e \in FIXDATE \tag{10}$$

$$DER_{r,d} \ge ER_{r,d} - ER_{r,d}^{old} \qquad \forall r,d \tag{11}$$

$$CER_{r,d} \ge ER_{r,d}^{old} - ER_{r,d} \qquad \forall r,d \tag{12}$$

$$ER_{r,d} \ge 0 \qquad \forall r,d \tag{13}$$

$$DER_{r,d} \ge 0 \qquad \forall r,d \tag{14}$$

$$CER_{r,d} \ge 0 \qquad \forall r,d \tag{15}$$

$$EXTRA_r \ge 0 \qquad \forall r \tag{16}$$

$$X_{e,o,d} \in \{0,1\} \qquad \forall e,o,d \tag{17}$$

$$Y_{c,d} \in \{0,1\} \qquad \forall c,d \quad (18)$$

$$R_{e,o,d,d'',k,r} \geq 0 \qquad \forall e,o,d,d'',k,r \quad (19)$$

Objective Function

The objective function maximizes a series of rewards while minimizing penalties that reflect the quality of the schedule produced, as well as its similarity to the existing schedule, if one exists. Initial values for penalties parameters (i.e., values on day 1 of the planning horizon, for terms with a *d* index) are set by the user. Time-varying penalties generally decay with time in order to reflect the fact that changes that occur far in the future are preferred over changes that occur in the very near term. For example, EODSKED may use $preq_{r,d} = preq_{r,init}\ \alpha^d$, where $preq_{r,init}$ is set by the user and α is a constant between 0 and 1.

The first part of the objective function captures the training value received by platoons and companies:

$$\sum_{\substack{e \\ o \in PLAT_e \\ d \in START_{e,o}}} we_{e,o,d} X_{e,o,d} + \sum_{c,d} wc_{c,d} Y_{c,d}$$

Factors impacting the quality of training received by a platoon are: (1) the timing of the training relative to the platoon's deployment date; (2) the pipeline in which the platoon trains, and (3) whether or not the platoon trains alongside another platoon in the same company, for those platoons that belong to companies. The term $\sum_{\substack{e \\ o \in PLAT_e \\ d \in START_{e,o}}} we_{e,o,d} X_{e,o,d}$ captures the first two factors. $X_{e,o,d}$ is an indicator variable used to denote platoon *e*'s enrollment in pipeline *o* starting on day *d*, while $we_{e,o,d}$ is a parameter denoting the reward for such enrollment. The term $\sum_{c,d} wc_{c,d} Y_{c,d}$ captures, the third factor impacting training quality; namely, pairing of platoons from the same company. $Y_{c,d}$ is an indicator variable that reflects the pairing of platoons from company *c* on day *d*, while $wc_{c,d}$ is a parameter that denotes the reward for such a pairing

The next set of terms capture penalties relating to resource usage:

$$-\sum_{r,d} pr_{r,d} ER_{r,d} - \sum_{k,r}\left(p_{k,r} \sum_{e,o,d,d''} R_{k,r,e,o,d,d''} \right) - \sum_{r} pe_r EXTRA_r$$

The term $\sum_{r,d} pr_{r,d} ER_{r,d}$ models shortages of resources. In certain cases a particular resource may not be available in sufficient supply to meet EODTEU TWO's training demands. When this occurs, EODSKED records any resource shortfalls using the $ER_{r,d}$ variable and penalizes them using the $pr_{r,d}$ parameter. This allows the user to requisition or otherwise acquire any additional resources that will be needed to execute the training schedule. The term $\sum_{k,r}\left(p_{k,r} \sum_{e,o,d,d''} R_{k,r,e,o,d,d''} \right)$ models substitutions among resources. Resource requirements are stated in terms of categories (*k*), while resource assignments are made from particular resource types (*r*). This allows EODSKED to capture substitutions among resource types and penalize them appropriately. For instance, if a particular training activity required a resource from the category *k*="Truck, Option 1," the resource types *r*="Truck, F-150" and *r*="Truck, F-350" might both be acceptable resources for fulfilling this need. However, if *r*="Truck, F-150" were preferred over "Truck, F-350," this would be reflected as $p_{\text{Truck, Option 1,Truck, F-150}} < p_{\text{Truck, Option 1, Truck, F-350}}$. The *EXTRA* term deducts a penalty when the average utilization rate of a resource exceeds 80% over the entire planning horizon.

The next set of terms begins the persistent region of the objective function and reflects changes to platoons' training schedules:

$$-\sum_{e}\left(pb_e \sum_{d'=0}^{d_e^{old}-1}\left(d'\sum_{o} X_{e,o,d_e^{old}-d'} \right) + pa_e \sum_{d'=0}^{H-d_e^{old}}\left(d'\sum_{o} X_{e,o,d_e^{old}+d'} \right)\right) - \sum_{c\in Y^{old}} pc_c(1-\sum_{d} Y_{c,d})$$

The penalties pb_e and pa_e reduce the objective value when a platoon begins training either before or after its original start date in the existing solution. The penalty pc_c is assessed if company *c* was paired in the existing solution and is not paired in the new solution.

The next term penalizes changes to resources that have been requisitioned in the existing solution:

$$-\sum_{r,d}\left(preq_{r,d} DER_{r,d} + pcreq_{r,d} CER_{r,d} \right)$$

Because it is undesirable to alter a requisition that is already in place, these terms penalize requisitioning of additional resources beyond what was already requisitioned in the existing solution ($DER_{r,d}$), as well as cancellation of resources already requisitioned in the existing solution ($CER_{r,d}$).. The variables $DER_{r,d}$ and $CER_{r,d}$ are known as *elastic persistent variables*. Elastic persistent variables have a target value and a linear penalty for deviating from the target (Brown, Dell, & Wood, 1997).

Finally, in the remaining terms assess penalties for changes that occur in the schedules of training personnel:

$$-\sum_{r\in PEOPLE,d'}\left(\left(ppw_{r,d'} - ppc_{r,d'}\right)\left(\sum_{k,e,o,d,d'':d'=d+d''-1} R_{k,r,e,o,d,d''} - ER_{r,d'}\right)\right)$$

If personnel resource r is assigned to work on day d' when r was not originally scheduled to work on day d', a penalty $ppw_{r,d'}$ decreases the objective value. On the other hand, if personnel resource r was assigned to work on day d' in the existing solution and is still assigned to work on day d', a reward $ppc_{r,d'}$ is added to the objective value. Thus, these terms reward the non-cancellation of work and penalize the cancellation of days off.

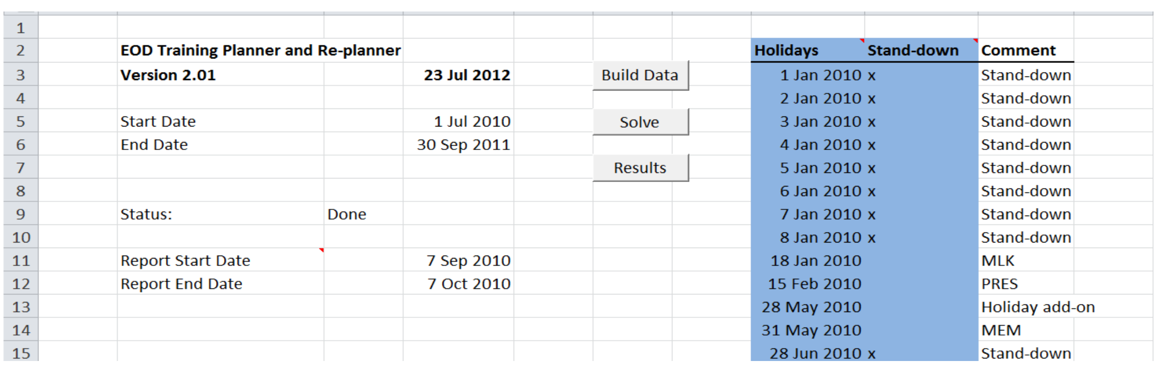
Constraints

Constraint set (1) requires a training option to be selected for each platoon within its permitted training window. Constraint set (2) sets a binary variable to indicate whether two platoons train together. The constants 0.6 and 0.4 prevent this variable from being activated by two "platoon-type" pipelines. Constraint set (3) ensures that a "company-type" pipeline is not utilized unless an appropriate "platoon-type" pipeline is also utilized, taking into account the number of teams trained by the "company-type" pipeline and the number of teams that need to be trained for the platoon. Constraint set (4) ensures that each platoon receives the required amount of resources in each category, on each day. Constraint set (5) measures any resources required in excess of what is available. Constraint set (6) ensures that at most 2 platoons start training on any day.

This is necessary in order to ensure that reward for training a company together is calculated correctly in constraint set (2). Constraint set (7) records aggregate resource utilization over 80%. Constraint set (8) ensures that the same resources are used on all days in which a pipeline operates in Rota, Spain. Constraint set (9) fixes a platoon's start date and pipeline to be the same as those in the existing solution, if the user has elected to fix these. Constraint set (10) fixes a platoon's start date to be the same as in the existing solution, if the user has elected to fix this. Constraint sets (11–12) record changes in excess resource utilization. Constraints (13)–(19) declare variable types.

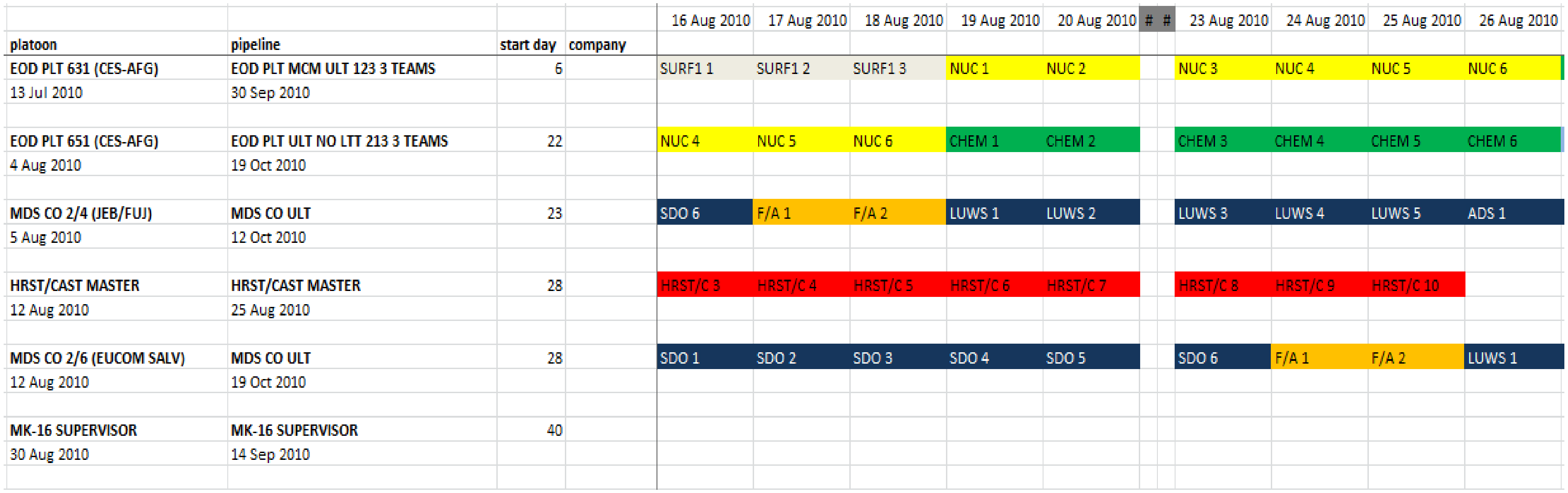
C. EODSKED USER INTERFACE

The user interacts with EODSKED via an Excel-based interface. The first worksheet in this interface is known as the Dashboard (Figure 3). The Dashboard contains the Build Data button, which imports data from several supporting worksheets designed to mirror worksheets currently used in the manual process. The Solve button executes an implementation of EODSKED written in the General Algebraic Modeling System (GAMS). Finally, the Results button writes the annual schedule to a Gantt chart (Figure 4) and creates a series of report worksheets that track resource consumption.



					Holidays	Stand-down	Comment
1							
2	**EOD Training Planner and Re-planner**				**Holidays**	**Stand-down**	**Comment**
3	**Version 2.01**		**23 Jul 2012**	Build Data	1 Jan 2010	x	Stand-down
4					2 Jan 2010	x	Stand-down
5	Start Date		1 Jul 2010	Solve	3 Jan 2010	x	Stand-down
6	End Date		30 Sep 2011		4 Jan 2010	x	Stand-down
7				Results	5 Jan 2010	x	Stand-down
8					6 Jan 2010	x	Stand-down
9	Status:	Done			7 Jan 2010	x	Stand-down
10					8 Jan 2010	x	Stand-down
11	Report Start Date		7 Sep 2010		18 Jan 2010		MLK
12	Report End Date		7 Oct 2010		15 Feb 2010		PRES
13					28 May 2010		Holiday add-on
14					31 May 2010		MEM
15					28 Jun 2010	x	Stand-down

Figure 3. Snapshot of the Dashboard worksheet for EODSKED user interface.



				16 Aug 2010	17 Aug 2010	18 Aug 2010	19 Aug 2010	20 Aug 2010	#	#	23 Aug 2010	24 Aug 2010	25 Aug 2010	26 Aug 2010
platoon	**pipeline**	**start day**	**company**											
EOD PLT 631 (CES-AFG)	**EOD PLT MCM ULT 123 3 TEAMS**	6		SURF1 1	SURF1 2	SURF1 3	NUC 1	NUC 2			NUC 3	NUC 4	NUC 5	NUC 6
13 Jul 2010	30 Sep 2010													
EOD PLT 651 (CES-AFG)	**EOD PLT ULT NO LTT 213 3 TEAMS**	22		NUC 4	NUC 5	NUC 6	CHEM 1	CHEM 2			CHEM 3	CHEM 4	CHEM 5	CHEM 6
4 Aug 2010	19 Oct 2010													
MDS CO 2/4 (JEB/FUJ)	**MDS CO ULT**	23		SDO 6	F/A 1	F/A 2	LUWS 1	LUWS 2			LUWS 3	LUWS 4	LUWS 5	ADS 1
5 Aug 2010	12 Oct 2010													
HRST/CAST MASTER	**HRST/CAST MASTER**	28		HRST/C 3	HRST/C 4	HRST/C 5	HRST/C 6	HRST/C 7			HRST/C 8	HRST/C 9	HRST/C 10	
12 Aug 2010	25 Aug 2010													
MDS CO 2/6 (EUCOM SALV)	**MDS CO ULT**	28		SDO 1	SDO 2	SDO 3	SDO 4	SDO 5			SDO 6	F/A 1	F/A 2	LUWS 1
12 Aug 2010	19 Oct 2010													
MK-16 SUPERVISOR	**MK-16 SUPERVISOR**	40												
30 Aug 2010	14 Sep 2010													

Figure 4. Sample Gantt chart created by EODSKED.

III. ANALYSIS AND RESULTS

A. ANALYSIS

To examine the strength of EODSKED as a planning tool, we evaluated the model with simulations that made changes to platoon end dates that are representative of possible schedule shifts encountered by the user. We focused on end date changes since they are the most common type of change encountered by EODTEU TWO. End dates for platoons moved five to 90 days either before or after the original end date. The simulations ran 129 different scenarios of date changes. We used nearly orthogonal Latin hypercube design to create the scenarios (Cioppa & Lucas, 2007). This design allowed us to test a range of possible end dates with a limited number of scenarios.

The experiments conducted on EODSKED used a baseline schedule adapted from actual operational input from EODTEU TWO in 2010 and 2011. It consists of eight EOD platoons, two of which belonged to a named company; two MDS companies; two EOD SOF companies; and six personnel training courses. These personnel training courses are conducted for the benefit of EODTEU TWO and other Navy personnel and are not associated with EOD platoons. However, they require resources also required by EOD platoons and thus need to be considered in the planning process. SOF companies trained in 20-day pipelines, while most other platoons trained in 51-day pipelines. In each of the scenarios simulated, each platoon was given a window of five to 39 feasible start dates between July 2010 and June 2011 centered its desired start date. Each optimization problem solved during the simulations runs contained about 175,000 constraints and 1.5 million variables, approximately 1,600 of which were binary. The computation time required to reach a 5% optimality gap ranged from 4 minutes to 9 hours; most problems were solved in five to 20 minutes using a 2.80 GHz Intel Core i7 CPU with 24 GB RAM.

We performed two analyses with the simulations. The first looked at the effect of user-selected penalties on specific changes to platoons. The second analysis examined the tradeoff in schedule quality resulting from inclusion of persistence terms.

1. Effects of User-Selected Penalties

We first studied the effects of user-selected penalties on specific types of changes in the schedule. The platoon-specific changes that were measured were:

- Number of platoons changing start date
- Maximum change in any platoon's start date
- Total change in all platoons' start dates

In this discussion, the term "platoon" refers to any entity undergoing training (including companies, Navy personnel, etc.).

The penalties we considered are summarized in Table 1 and reflect the interests of different entities in the scheduling problem. In addition to a *baseline* penalty profile developed following discussions with subject matter experts at EODTEU TWO, we tested *platoon-centric*, *personnel-centric* and *resource-centric* penalties. Platoon-centric penalties heavily penalize changes to platoons' start dates and breakups of companies. Personnel-centric penalties discourage changes to the schedules of EODTEU TWO personnel, while resource-centric penalties discourage changes to requisitioned resources. To establish upper and lower bounds on performance, we also solved an optimization problem to determine a lower bound for each of the three specific measurements of platoon date change, and we optimized the schedule without including persistence terms as denoted in the second column of Table 1.

Penalty	Without Persistence	Baseline	Personnel-centric	Resource-centric	Platoon-centric
$ppw_{r,d}$	0	500/d	3000/d	125/d	125/d
$ppc_{r,d}$	0	250/d	3000/d	65/d	65/d
$preq_{r,d}$	0	150/d	25/d	3000/d	25/d
$pcreq_{r,d}$	0	150/d	25/d	3000/d	25/d
pa_e	0	500	200	200	1000
pb_e	0	600	150	150	1000
pc_c	0	300	50	50	500

Table 1. Summary of penalties for simulation runs.

a. Results

Number of Platoons Changing Start Date

A change to a platoon's start date is disruptive to both the platoon and EODTEU TWO; thus, it is important to consider the number of platoons changing their start date in a proposed schedule. Figure 5 shows the average number of platoons changing start date over all scenarios for each set of penalties. We see that the average number of platoons changing start date is lower for both the platoon-centric and resource-centric penalties than for any other penalties. This is a reasonable result, as shifting a platoon's start date also changes its resource requirements. Figure 6 shows the number of platoons changing start date in each scenario, where the scenario order is sorted according to the value of the lower bound. As Figure 6 indicates, different penalties perform better in different scenarios, but any non-zero set of penalties improves the quality of the schedule with respect to the number of platoons changing start dates.

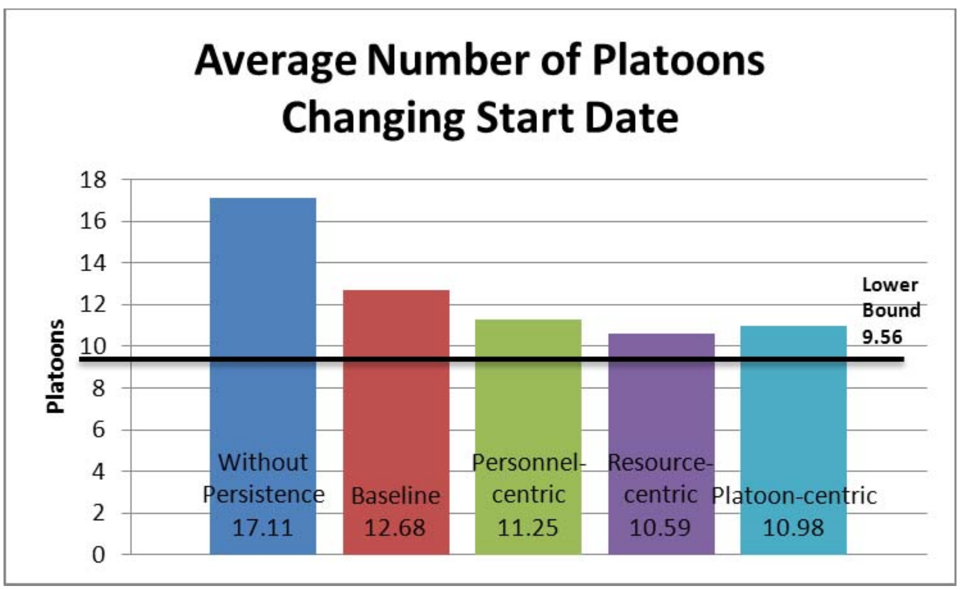


Figure 5. Average number of platoons changing start date for all scenarios.

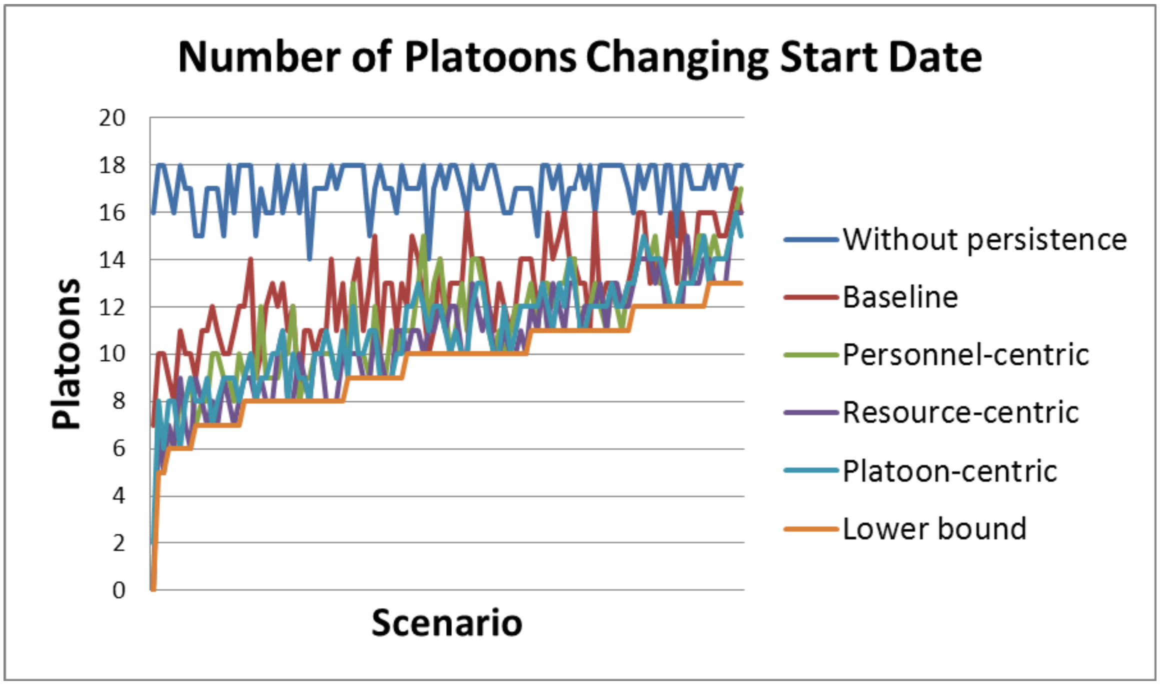


Figure 6. Number of platoons changing start date in each scenario.

Maximum Change in Platoon Start Date

Another important figure of merit is the maximum amount by which any platoon's start date changes. As shown in Figures 7 and 8, the platoon-centric penalties perform the best by a small margin according to this metric. Although this change is not specifically optimized in the model, penalties that discourage changes to platoons' start dates also have the effect of minimizing the maximum change incurred by any platoon. Again, the scenarios in Figure 8 are sorted according to their lower bounds and do not necessarily appear in the same order as in Figure 6.

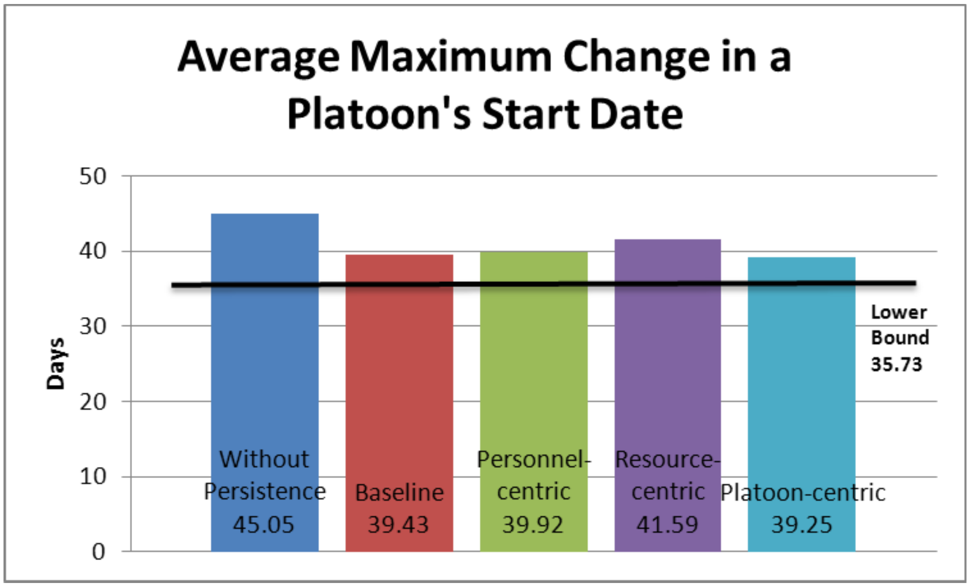


Figure 7. Average maximum change in a platoon's start date.

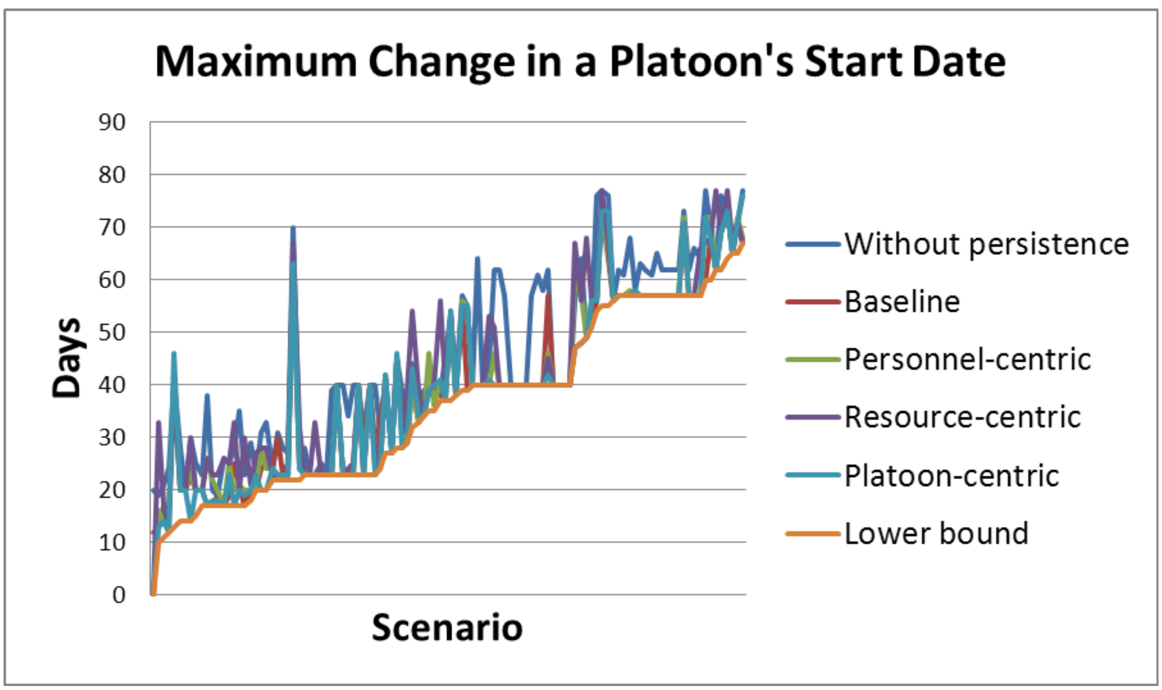


Figure 8. Maximum change in a platoon's start date for all scenarios.

Total Change in Platoon Start Dates

A final figure or merit is the total change to all platoons' start dates. Figures 9 and 10 show the ability of the penalties to impact this quantity. This quantity is directly optimized by EODSKED; thus, one would expect that persistence modeling would have a dramatic effect on the outcome. Indeed, the platoon-centric penalties yield, on average, nearly a 50% reduction in the total change to platoon start dates relative the model that does not incorporate persistence. As before, any set of penalties yields better results than zero penalties. Again, scenarios in Figure 10 are sorted according to their lower bounds; they do not necessarily appear in the same order as in Figures 6 and 8.

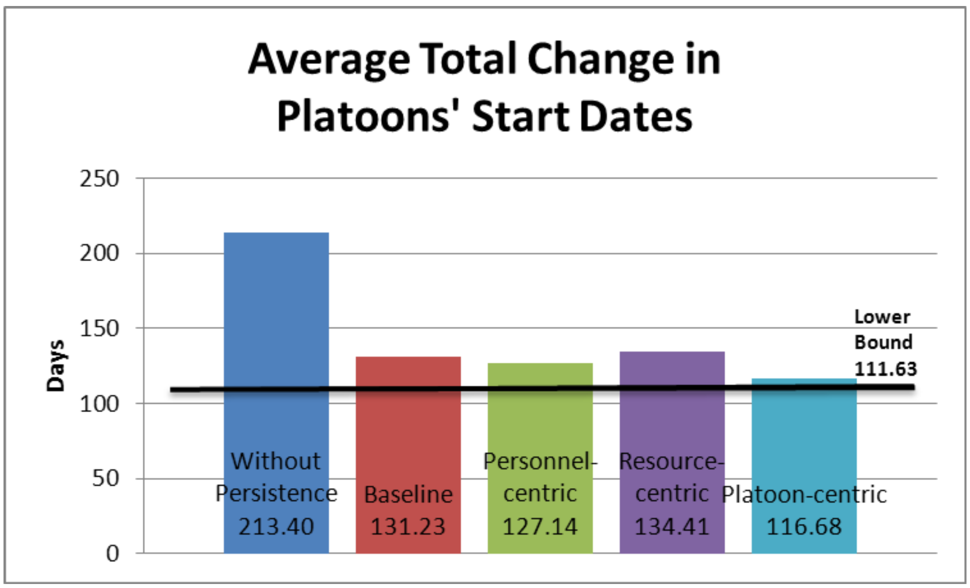


Figure 9. Average total change in platoons' start dates.

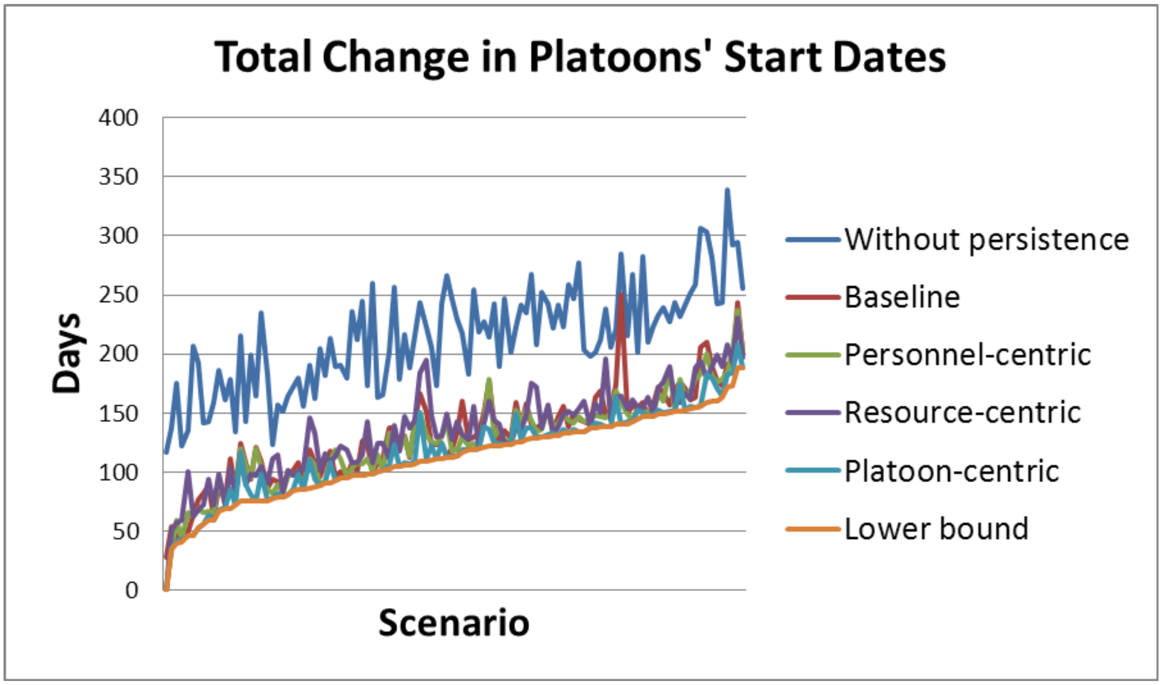


Figure 10. Total change in platoons' start dates. Note significant reduction in number of days with the use of persistence.

2. Cost of Persistence

The second set of simulations compared optimal objective values with and without persistence. To obtain values without persistence we ran the simulations with the persistence terms removed from the objective function. Specifically, we removed terms that penalize deviations from the original schedule. For model runs that included persistence terms in the objective function, we calculated objective values both including and excluding persistence terms in post-processing. Comparing the objective values of the model with persistence terms to values without persistence terms shows what effects perturbations to a schedule would have on overall training value. Lower objective values for runs in which persistence terms were included indicate that consideration of persistence is detrimental to the overall solution quality according to metrics other than persistence. The goal of this analysis was to see if the addition of the persistence terms could minimize the overall impact of these perturbations. This also highlights how shifts in specific platoon's dates could improve or reduce the optimal objective value.

a. Results

We used partition trees to analyze the data from the simulation runs. This form of analysis helps isolate factors that cause high degrees of variation in the optimal objective values. There was no strong linear relationship between the amount of days changed and objective function value. The optimal objective values were worse with high variance in platoon start dates. For example, if two platoons that had been formed as a company now had large separation in their start dates, this was worse than if both platoons were shifted by a large amount together. Compared to the simulations without persistence terms, the simulations containing persistence terms had a larger variance and higher optimal objective values on average. There was a mild positive correlation between scenarios that had higher objective values without persistence in that the same scenarios also had higher objective values with persistence.

Some scenarios demonstrate that persistence terms had a major effect. For instance, one scenario showed minor changes to any category with persistence terms included but a significant increase in changes without persistence. The number of platoons changing start date increase from 2 with persistence to 15 without and the total change in platoons start dates increased from 2 with persistence to 79 without.

IV. CONCLUSIONS AND FUTURE WORK

A. CONCLUSIONS

EODSKED has the ability to produce an optimized training schedule that maximizes training value by efficiently utilizing limited training resources. The schedule created by EODSKED can overcome some of the limitations that are encountered in the manual process. EODSKED also gives the user the ability discover efficiencies in the way the schedule is organized and in the use of resources.

Experiments testing the impact of changes on generated schedules show that by incorporating persistence, EODSKED maintains a robust and flexible schedule. Penalties and rewards allow the user to emphasize the importance of specific attributes of the schedule, thus shaping its overall quality.

B. FUTURE WORK

The modeling approaches used in EODSKED are very general; and with some modification, a version of this tool could be used in many different scheduling problems. In particular, EODSKED could easily be modified and applied to types of training that include class or group modules with resource and time constraints. An area of future research involves the application of this model to other Navy training pipelines, such as flight training or nuclear power training. EODSKED could even be adapted to work with flight or ship scheduling. In these cases, persistence would be required to attempt to minimize the effect of changes on these generally dynamic types of problems. In the near term, plans exist to extend EODSKED's usage to plan the training modules completed by EOD platoons prior to their arrival at EODTEU TWO.

The simulation experiments carried out in Chapter III focused on the impact of changes to platoon's target end dates. However, it is also of interest to examine the effect of large changes to resource constraints on the objective function. Future work could examine the impacts of the loss or reduction in manpower or materiel resources to overall training value. This could assist EODTEU TWO in possibly identifying resources essential for the completion of training or resources that are being underutilized.

Further experimentation could also examine the worst-case impact of a failure to model persistence. Consider an initial schedule S_0 that must accommodate some perturbation to its input data. One might imagine producing a revised schedule S_1 by optimizing without consideration of persistence terms. The optimal objective value of S_1, z_1*, would then reflect the quality of the best possible schedule that could be created without considering persistence. Next, in order to find the worst-case impact of a failure to consider persistence when modifying S_0, one could solve for the schedule S_2 with the *maximum* number of changes to platoon start dates, resource consumption, etc, subject to the constraint that the quality of S_2 is close to that of S_1, as measured by the values of the non-persistent objective terms as recorded in z_1*.

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